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Assessing climate change impacts on cereal production: The role of fertilizer use and GMM-based estimation

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ABSTRACT

Environmental hazards cause a decline in food production, leading to food crises and overall instability among different nations. This scenario is more prevalent in the case of cereal production in some developing countries, particularly in South Asian regions. In line with this, research has been conducted to examine the impacts of climate change variables (rainfall, temperature, carbon dioxide emissions, methane emissions, nitrous oxide emissions) and control variables such as cereal production and fertilizer use on cereal output. The analysis considers cereal productivity while incorporating secondary data. A two-step Generalized Method of Moments (GMM) approach has been applied, considering eighteen top productive countries as dependent variables, with climate variables and control variables to analyze their connectivity. The study found that climate change variables significantly affect cereal production across the sample countries, except for methane emissions. Additionally, fertilizer use contributes to increased cereal crop yields. The findings are valuable for policymakers to identify specific negative effects of climate variables and adopt effective strategies to enhance cereal production. Ultimately, updating policies, applying modern farming techniques, and employing skilled human resources should be prioritized to address these challenges.

Contribution/Originality: This study contributes by analyzing the robust relationship between climate change and cereal production using dynamic GMM estimation. We examine the effects of multiple climate change variables across leading crop-producing countries. The study highlights fertilizer usage and the area under cereal production as key adaptation strategies, incorporates production dynamics, and offers methodological improvements.

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1. INTRODUCTION

Climate change poses a serious danger to agricultural productivity, especially in developing nations where agriculture is essential for economic growth, employment creation, and food security (Arora, 2019; Aryal et al., 2020).

One-fifth of the world's population lives in South Asia, but they occupy about 5% of the world's arable land, where agriculture is still the main livelihood. Moreover, more than two-thirds of the region's population live in rural areas, indicating their dependence on agriculture as their main source of income (Almazroui, Saeed, Saeed, Islam, & Ismail, 2020; Bandara & Cai, 2014). Although we live in an era of advanced technology that ensures high crop production through the optimal use of fertilizers and seeds, climate change continues to pose serious challenges to agriculture in the region (Chandio et al., 2021). For example, high variability in temperature and rainfall patterns is having a significant impact on agricultural productivity and sustainability in South Asia (Alam, 2017; Kogo, Kumar, & Koech, 2021; Masters, Baker, & Flood, 2010). Therefore, addressing these climate-related challenges is essential to safeguard the sustainability of agriculture and livelihoods in the region.

Adverse climate change is causing high crop losses, low yields, and high production costs, which are adversely affecting their income levels (Pulighe et al., 2024; Shamshad, Nawaz, Khan, & Arif, 2024). Clearly, income from agricultural livelihoods such as crop production and livestock rearing is being directly affected by climate variables, namely temperature variations, changing rainfall patterns, and elevated CO_2 levels (Verma et al., 2025). Additionally, floods, droughts, and socio-economic disasters are also common in tropical and subtropical regions due to rising temperatures and water demand (Ekele et al., 2025; Palmer et al., 2023). Other difficulties include erosion, loss of soil fertility due to the use of chemicals or pesticides, and traditional farming practices (Chatterjee et al., 2021). Therefore, a wake-up call for climate-resilient agricultural practices is needed in this region.

Climate change is severely affecting low- and middle-income countries, and about fifteen percent of their GDP depends on climate-sensitive agriculture (World Bank Group, 2019). Global economic productivity is forecast to decline by 4% by 2050 in low- and lower-middle-income countries, with the decline being more severe in South Asia (Jones, 2022). Measuring the impact of climate change on cereal production in this region is a must to develop appropriate policy responses (Chuang, 2019). Therefore, exploring these climate factors and their impacts is essential to developing effective strategies to increase resilience and ensure food security in vulnerable agricultural economies.

Bangladesh, one of the top crop-producing countries in South Asia, where agriculture contributes 14.2% to the national GDP, is already facing political, economic, and environmental challenges (World Bank Group, 2017). CO2 emissions per capita in Bangladesh increased from 0.11 metric tons in 1985 to 0.53 metric tons in 2016 (Ahmed, 2018). The country's cereal production, particularly rice, is highly vulnerable to weather fluctuations (Islam, Alam, Begum, Sarker, & Bhandari, 2022; Joseph et al., 2023). Rice production is particularly vulnerable to droughts and floods as a result of declining yields caused by rising temperatures and changes in rainfall patterns (Dasgupta, Hossain, Huq, & Wheeler, 2014; Hussain, 2011). It is estimated that the productivity of major crops will decline by 5-13 percent by 2030 due to climate vulnerability (Bandara & Cai, 2014). Therefore, Bangladesh needs to adopt climate-resilient agricultural strategies to ensure food security amidst climate change.

Recent studies have used various methods to examine how climate change affects crop yields. Evidently, Chandio, Jiang, Rehman, and Rauf (2020) found that while higher CO_2 levels may increase agricultural productivity in the short run, temperature fluctuations and rainfall have a long-term adverse impact. However, Pickson, He, Ntiamoah, and Li (2020) revealed that high temperatures and CO_2 levels negatively affect cereal production in China. Other studies also confirm that CO_2 has both long-term and short-term effects on cereal yields (Ahsan, Chandio, & Fang, 2020). These findings emphasize the necessity for adaptable farming methods to mitigate climate change's effects on crop production.

Most studies examine climate change's impact on crop production using time-series or panel data (Rahim & Puay, 2017). However, this study applied the Generalized Method of Moments (GMM) to a panel dataset of the top 18 productive countries from 2019 to 2020. This method allows for a dynamic model that addresses endogeneity and minimizes cross-country scale differences. We explain the impact of climate change on crop production in these selected countries, controlling for fertilizer use and arable land to reduce selection bias.

2. REVIEW OF LITERATURE

2.1. Theoretical Framework

This research is grounded in multiple theoretical frameworks that explain the complex interactions between climate change and agricultural productivity, especially crops. Climate change impact theory shows how climatic factors such as temperature and precipitation have a direct impact on crop production. These environmental factors cause changes in seasons, soil fertility, and plant anatomy, which impact crop production (Lobell, Schlenker, & Costa-Roberts, 2011). In addition, the Environmental Kuznets Curve (EKC) hypothesis is used to explain how greenhouse gas emissions affect agriculture in two ways. This means that there is an inverted U-shaped relationship between economic growth and environmental damage. Also, pollution levels usually increase when the economy moves towards growth, but they decrease as technology improves and people become more aware of the environment (Dinda, 2004). Other variables like methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) emissions are examined.

To explore the economic aspect, previous studies are based on the theory of the agricultural production function, which holds that food grain output is a product of input combinations (including fertilizer usage and cultivated area). These covariates have a direct effect on production and reduce the bias of the estimates due to unobserved environmental or socioeconomic variables (Coelli, Rao, O'Donnell, & Battese, 2005; Dai, 2025). The theory of technological change in agriculture predicts that the negative impacts of climate change on crop productivity can be mitigated by adopting adaptation measures, such as improving fertilizer use efficiency (Schultz, 1964). As the Sustainable Livelihood Framework (SLF) states, the availability of institutions, technologies, and resources can improve the sustainability and resilience of rural livelihoods (Chambers & Conway, 1992). Thus, the theoretical basis indicates the institutional support, technological innovation, and input optimization required for climate-resilient crop production systems and rural livelihoods.

Indeed, within the framework of agroecosystem resilience theory, it has been postulated that an agricultural system should become resilient (i.e., able to generate yield even under harsh or changing environmental conditions) (Folke, 2006). Fertilizer buffer found in this study is an example of resilience tactics. Finally, although econometric theory (omitted variable bias and confounding) provides evidence that omitting relevant control variables (land area or fertilizer use) can lead to biases in effect estimates for climate-related variables on agricultural output (Wooldridge, 2020). Thus, including these variables enhances the empirical validity of hypotheses.

These perceptions of the above theories provide a comprehensive framework for analyzing climate change related to environmental, economic, and methodological aspects of cereal production. Therefore, a cross-functional approach combining agricultural economics, environmental science, and climate modeling is necessary to measure the effects of climate change on grain production. Fundamental elements of this framework include relationships between climate variables (e.g., precipitation, temperature, CO_2 concentration), agricultural inputs (e.g., fertilizer, land use), and crop production (Berhane, 2018; Saud et al., 2022). Thus, changes in climate, such as rainfall and temperature, and indirect consequences, such as soil erosion, insect outbreaks, and water availability, must be captured (Alotaibi, Alhajeri, Al-Fadhli, Al Jabri, & Gabr, 2023). Besides, the framework aims to consider human activities, such as the use of fertilizer, which have the capacity to decrease or increase the impact of climate change on crop productivity (Crane-Droesch, 2018). Therefore, to calculate past data, predict future trends, and develop climate-resilient agricultural policies, sophisticated statistical methods are necessary.

Use of advanced econometric methods to overcome omitted variable bias, endogeneity, and spatial autocorrelation to ensure analytical rigor is required under this framework. Incorporating crop simulation, cross-sectional analysis, partial, and general equilibrium models can offer a holistic view of the agricultural system under the climate crisis (Delince, Ciaian, & Witzke, 2015). In addition, it needs to remember that fertilizer use is intrinsic and influenced by weather and crop performance. Effective assessment of fertilizer performance requires instrumental variables and simultaneous equations. The methodology should also consider regional crop types and climate vulnerability and assess the cost-effectiveness of adaptation options (Georgopoulou et al., 2017). Identifying the role of fertilizer use during climate change is central to sustaining agricultural productivity, given the upward global food demand (Farah, Mohamed, Musse, & Nor, 2025; Islam, 2025). Eventually, a strong interdisciplinary framework helps us better understand how climate change impacts cereal production and supports the development of practical, empirically supported adaptation and mitigation strategies to guarantee global food security.

2.2. Previous Empirical Literature Evidence

Empirical research on climate change and crop production demonstrates that climatic factors and agricultural productivity have an intricate relationship. Temperature and precipitation are the most frequently studied aspects of the climate in Asia, Europe, Africa, and Latin America. They frequently lower crop yields, particularly in harsh environments. For instance, Singh, Arora, and Chandra Babu (2024) used ARDL, finding that rising temperatures significantly reduce cereal output, while rainfall has a positive but diminishing impact. Remarkably, Ma, Karimi, Mohammed, Shahzadi, and Dai (2024) also emphasized the role of fertilizer use in increasing crop yield, which is closely consistent with the aim of this study.

Similarly, inconclusive empirical evidence from Africa also underscores a positive rainfall effect but emphasizes the high vulnerability of the cereal production process to temperature variability and CO_2 emissions (Pickson, Boateng, Gui, & Chen, 2024; Sissoko et al., 2023). These studies highlight the need for focused adaptation measures, such as farmer support policies and climate-resilient technologies, particularly in rainfed areas. Meanwhile, Kelkouli, Bouderbala, and Haddad (2024) decoded a significant drop in crop production in Algeria due to the shortfall of rainfall, reinforcing the importance of water availability and irrigation infrastructure.

Research in developed regions such as the EU adds a different dimension: despite technological advancements, yield stagnation linked to heat and drought stress has begun to erode the climate mitigation benefits of cereal farming (Łącka, Supron, & Szczepaniak, 2024; Riedesel et al., 2024). These findings suggest that adaptation may not be keeping pace with climatic shifts, and that location-specific soil quality and energy consumption patterns play crucial roles. Methane and nitrous oxide, though less frequently assessed, are gaining traction. For example, Magazzino, Gattone, Usman, and Valente (2024) and Zhang, Waldhoff, Wise, Edmonds, and Patel (2023) incorporate agricultural emissions into broader sustainability discussions, showing that excessive emissions contribute to declining yields and compromise food security, even when technological innovation is high.

While many studies rely on time-series econometrics (ARDL, FMOLS, cointegration), a growing number integrate panel data methods that account for cross-sectional dependence and heterogeneity (e.g., (Łącka et al., 2024; Pickson et al., 2024)), offering more robust insights for multi-country analyses. However, gaps remain in fully modeling fertilizer dynamics, especially their interaction with emissions. Most analyses treat fertilizer as a control rather than a focal variable, leaving room for this study to make a significant contribution by exploring its mitigating potential amid climate-induced stressors.

In summary, prior studies confirm the detrimental effects of climate change on cereal production, while pointing to technology and input use, especially fertilizers as promising avenues for resilience. Yet, few works explicitly model the interaction between fertilizer application and environmental emissions in a cross-country framework (Gyamerah, Asare, Mintah, Appiah, & Kayode, 2023; Pickson et al., 2024; Rötter, Hoffmann, Koch, & Müller, 2018; Singh et al., 2024; Stadnik, Tobiasz-Salach, & Migut, 2024). This highlights a critical research gap that this study is well-positioned to address.

Despite the extensive body of empirical work, few studies systematically incorporate a multi-country, multi-year panel framework that captures both climatic and agronomic factors in tandem, particularly those related to fertilizer dynamics (Baris-Tuzemen & Lyhagen, 2024; Łącka et al., 2024; Magazzino et al., 2024). The prevailing focus on single-country analyses or simplified aggregate measures often limits their generalizability and policy relevance (Ali, Dahir, & Yusuf, 2023; Massagony, Tam Ho, & Shimada, 2022). Thus, empirical findings remain inconclusive.

Consequently, this creates a significant gap in understanding how crop production systems can protect themselves from the impacts of climate change in different agroecological regions. Filling this gap is essential, as it informs both local and global programs designed to ensure food security and promote climate-resilient agriculture. This study fills a gap by providing a comprehensive and policy-relevant analysis that links climate risks to production-based solutions, providing practical insights for sustainable agricultural planning.

3. ECONOMETRIC MODEL

For dynamic panel data, the system generalized method of moments (GMM) is more fitted to estimate the relationship (Arellano & Bover, 1995). Consider the following regression equation.

$$CP_{it} - CP_{it-1} = (\alpha - 1)CP_{it-1} + \beta 0 CV_{it} + \mu_i + \varepsilon_{it} \quad (1)$$

Where CP_{it} is the cereal production, $CP_{it} - CP_{it-1}$ is the rate of cereal production growth, CP_{it-1} is the initial level of cereal production, CV_{it} represents a vector of explanatory variables, μ_i is an unobserved country-specific effect, ε_i is the error term, and the subscripts i and t represent country and time period, respectively. Rewriting (1), we obtain.

$$CP_{it} = \alpha\, CP_{it-1} + \beta 0\, CV_{it} + \mu_i + \varepsilon_{it} \quad (2)$$

To eliminate country-specific effects, we take first differences of (2).

$$CP_{it} - CP_{it-1} = a(CP_{it-1} - CP_{it-2}) + \beta 0(CV_{it} - CV_{it-1}) + \varepsilon_{it} - \varepsilon_{it-1} \quad (3)$$

Levine, Loayza, and Beck (2000) suggest the use of instruments for two reasons: to address the likely endogeneity of cereal production and climate variables adoption, and because, by construction, the new error term ($\varepsilon_{it} - \varepsilon_{it-1}$) in the above equation is correlated with the lagged dependent variable ($CP_{it-1} - CP_{it-2}$).

3.1. Variables and Data

For the effect of climate change, unlike others, we used multiple variables to measure the impact on cereal. Some previous studies used only rainfall as a climate variable to measure the climate effect on cereal production (Wakjira et al., 2021). CO_2 is also a commonly used climate proxy in many studies (Onour, 2019). Furthermore, GHGs, e.g., methane and nitrous oxide emissions, are also common proxies to establish the relationship between climate change effects and cereal production (Simionescu, Bilan, Gędek, & Streimikiene, 2019). In some recent studies, researchers commonly used rainfall and drought (Ayanlade, Radeny, Morton, & Muchaba, 2018); rainfall and temperature (Amin, Zhang, & Yang, 2015; Eder, Salhofer, & Quddoos, 2024; Quiroga & Iglesias, 2009); rainfall, temperature, and CO_2 (Köprücü & Acaroğlu, 2023; Xiang & Solaymani, 2022); rainfall, temperature, radiation, and CO_2 (Xiong et al., 2010) as climate change to estimate cereal production.

Some studies used control variables besides the climate variables to capture the result (Chandio et al., 2021). Most of the existing studies are country-specific and use time series data. There are very few studies that use panel data to establish the relationship between cereal production and climate change, where one study considers lower-middle-income countries (Kumar, Sahu, Kumar, & Ansari, 2021), one study considers East Africa (Abdi, Warsame, & Sheik-Ali, 2023), and another study considers Asian countries (Ozdemir, 2022). The majority of the studies are based on FMOLS, FGLS, and ARDL models for analyzing panel data. The dynamic panel system-Generalized Methods of Moment (GMM) estimator developed by Arellano and Bover (1995) and Blundell and Bond (1998) which is more suitable for analyzing dynamic panels because it can address concerns about identification, account for lagged responses to any exogenous shock, reverse causality, and help to obtain unbiased parameters (Bond, Bowsher, & Windmeijer, 2001; Hauk Jr & Wacziarg, 2009). The use of the two-step system GMM is missing in the existing literature to measure the effect of climate change on cereal production.

Previous research shows empirical insights into the impact of various climate variables on cereal production, often based on data from diverse country groups. However, these studies typically overlook cereal (land) productivity. Moreover, none have concurrently examined the effects of rainfall, temperature, carbon dioxide emissions, methane emissions, and nitrous oxide emissions as climate variables while also including the area under cereal cultivation and fertilizer use as control variables. This study aims to fill that gap and add to the existing body of empirical evidence.

This study utilizes a strongly balanced panel dataset covering 18 countries with high cereal (land) productivity, each surpassing a productivity threshold of 0.2 (refer to Appendix, Table 1a) over the period 2016 to 2020. Data spanning 18 countries across 5 years were analyzed. The System GMM estimation method was employed for the analysis. Secondary data were sourced from the World Development Indicators (WDI) and the Climate Change Knowledge Portal (CCKP). The study examines the impact of climate-related variables, including rainfall (RF), temperature (TEM), carbon dioxide emissions (CO_2), methane emissions (ME), and nitrous oxide emissions (N_2O), on cereal production (CP) in countries with high agricultural land productivity. Additionally, the area under cereal cultivation (CL) and fertilizer use are included as control variables. A detailed description of the variables and data sources is presented in Table 1.

Table 1. List of study variables for the analysis.

V-abbreviations	Full-form	Units	D-source
CP	Cereal production	Metric Tons (In Lac)	WDI
RF	Rain Fall	Millimeter	CCKP
TEM	Temperature	Degree Celsius	CCKP
CO_2	Carbon dioxide	Kilotons (In Lac)	WDI
ME	Methane emissions	Thousand metric tons of CO_2 equivalent (In lac)	WDI
N_2O	Nitrous oxide emissions	Thousand metric tons of CO_2 equivalent (In Lac)	WDI
CL	Area under cereal production	Hectares	WDI
FER	Fertilizer	Kilograms per Hectare of Arable Land	WDI

Note: WDI-World development indicators, CCKP-Climate change knowledge portal

4. RESULTS

4.1. Descriptive Statistics and Correlation Analysis

Table 2 illustrates the descriptive statistics of the variables in the model to be measured. The table shows the mean, median, maximum value, minimum value, variance, standard deviation, skewness, and kurtosis of the variables. In this descriptive analysis, the standard deviation of each variable is high, indicating that the data under the variables are more scattered, which arises mainly due to considering different sizes (in terms of agricultural land area) of countries in the world. Additionally, all the variables are positively skewed, but in the case of kurtosis, carbon dioxide, methane emission, nitrous oxide emission, and the area under cereal production are highly peaked. The descriptive analysis (Table 2) and correlation analysis (Table 3) of these variables are given below.

Table 2. Descriptive statistics.

	CP	RF	TEM	CO_2	ME	N_2O	CL	FER
Mean	1080	1065.558	17.300	11.670	0.935	0.602	205	206.735
Median	381	776.510	14.540	2.670	0.495	0.229	81.313	166.818
Maximum	6170	3176.990	27.490	109	5.022	3.565	1020	574.182
Minimum	140	10.850	7.770	0.210	0.025	0.057	23.377	18.743
Variance	2.79e+11	505466.900	50.132	6.41e+07	1.61e+05	8.04e+04	9.07e+09	18093.270
Std. deviation	1670	710.962	7.080	25.310	1.260	0.897	301	134.511
Skewness	0.918	0.918	0.153	2.920	2.148	2.109	2.007	1.153
Kurtosis	3.097	3.097	1.273	10.623	6.698	6.250	5.410	3.470

Table 3. Correlation analysis.

Variables	CP	RF	TEM	CO_2	ME	N_2O	CL	FER
CP	1							
RF	-0.150	1						
TEM	-0.281	0.574	1					
CO_2	0.951	-0.183	-0.3697	1				
ME	0.800	-0.0399	0.0757	0.6596	1			
N_2O	0.971	-0.172	-0.2203	0.9237	0.8895	1		
CL	0.920	-0.090	-0.084	0.8264	0.9605	0.970	1	
FER	0.226	-0.064	0.164	0.325	0.099	0.241	0.186	1

4.2. Analysis of GMM for Dynamic Panel Data

Table 4 shows the different types of GMM model results to identify climate change's impact on cereal production in various countries. We use the Hansen and Sargan tests for the validity of instruments, and the residuals or error terms are not correlated with the instrument variables, respectively. Again, AR(1) and AR(2) tests justify the error term's first-order and second-order autocorrelation/serial correlation. The findings from the two-step system GMM model validate that the model is well-specified, as shown by the F-test (Prob > F = 0.000), indicating a strong overall fit. The Hansen test (Prob > chi^2 = 0.465) endorses the appropriateness of the instrumental variables used. Similarly, the Sargan test (Prob > chi^2 = 0.002) supports the validity of the over-identifying restrictions across all model specifications. Additionally, the AR(2) test result (Pr > z = 0.16) indicates that there is no second-order autocorrelation evidence found for further validating the model's reliability.

The result of the two-step system GMM shows a consistent but insignificant negative relationship between rainfall (RF) and cereal production. The result indicates that, on average, a percentage increase in rainfall leads to a 71.96662-unit decrease in cereal production, with other factors remaining constant. Previous research has demonstrated that rainfall can have both positive and negative effects on cereal production. Kumar et al. (2021) found that rainfall has a positive effect on cereal production; on the other hand (Eder et al., 2024) found out the negative influence on cereal production. Again, another climate variable, a negative and statistically significant impact of temperature (TEM) on cereal production is reported, which indicates that temperature has marginally led to a decrease in cereal production in the studied countries.

The results disclose that, on average, a 1% increase in temperature results in a decrease of 288,304.2 units in cereal production, assuming other factors remain unchanged. This finding aligns with the study by Xiang and Solaymani (2022), which reported that a 1% rise in temperature corresponds to a 2.87% reduction in general cereal production and a 3.52% decline in projected estimates. Additionally, the analysis illustrates a negative and statistically significant effect of carbon dioxide (CO_2) on cereal output. Specifically, a 1% increase in CO_2 emissions leads to an average decrease of 4.493874 units in cereal production, holding other variables constant. This result is consistent with existing empirical studies, such as Chandio et al. (2021), who found that CO_2 has an adverse impact on cereal production in both the short and long term.

Again, the system GMM results for Greenhouse Gas (GHG) emissions, specifically methane (CH_4) and nitrous oxide (N_2O), indicated a statistically significant positive and negative impact on cereal production, respectively. The results showed that, on average, a percentage increase in methane led to a 90.54769-unit increase in cereal production, while a percentage increase in nitrous oxide resulted in a 254.8543-unit decrease, with all other factors held constant. Simionescu et al. (2019) showed that GHGs have a positive influence on cereal production. On the other hand, Thapa, Chatterjee, Awale, McGranahan, and Daigh (2016) proved that nitrous oxide has negatively impacted cereal production.

The model illustrated that the control variable, a positive and statistically significant impact of fertilizer (FER) on cereal production, is reported, which indicates that fertilizer has marginally led to an increase in cereal production in the studied countries. The results indicated that, on average, a percentage increase in fertilizer leads to a 12,111.79-unit increase in cereal production, with other factors remaining constant. This result is proved by Yousaf et al. (2017), who showed that the use of mineral fertilizer can increase rice production from 19% to 41% and rapeseed production from 61% to 76%. Another control variable, a negative and statistically insignificant impact of the area under cereal production (CP) on cereal production, is reported, which indicates that the area under cereal production has marginally led to a decrease in cereal production. This result is proved by Harini, Ariani, Supriyati, Satriagasa, Susilo, and Giyarsih (2018), who examined that in North Kalimantan Province, where the agricultural land area increased while the agricultural production decreased.

Table 4. Stamatis and dynamic panel estimation, over the period 2016 to 2020.

Variables	POOLED OLS	DIFF-1 GMM	DIFF-2 GMM	SYS-1 GMM	SYS-2 GMM
CP	0.811***	-0.067	-0.098	1.055***	1.149***
RF	1542.490	790.534	568.952	206.661	-71.967
TEM	165211	-1748902	-2107256	-186537.100	-288304.200**
CO_2	-2.993	11.002	11.851**	-3.157	-4.494***
ME	-182.838**	-601.731	-527.731***	18.260	90.548*
N_2O	423.413**	1110.147***	1325.551***	-141.368	-254.854**
CL	0.726**	1.930**	1.845***	0.288	-0.073
FER	-8522.470	-95568.060*	-47022.890	14854.620	12111.790*
Constant	-2006650	1.01e+08*	6.31e+07*	-1141438	842353.500
Observations	72	72	12	72	72
Countries	18	18	18	18	18
Instrument		11	11	12	12
F-state(p-value)	0	0	0	0	0
Sargan		0.002	0.002	0.002	0.002
Hansen			0.281		0.465
AR(1)		0.079	0.62	0.004	0.06
AR(2)		0.078	0.201	0.004	0.16

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$ show statistical significance at 1%, 5%, and 10% level, respectively.

5. CONCLUSION AND POLICY IMPLICATIONS

This study analyzed the impact of climate change on crop production in 18 top crop-producing countries known for their high land productivity in crop cultivation from 2016 to 2020. The analysis utilizes a two-step system GMM estimator to address various econometric issues, including serial correlation, panel group-wise heteroscedasticity, cross-sectional dependence, and heterogeneity. Climate change is influenced by average annual rainfall, temperature, and emissions of CO_2, CH_4, and N_2O.

The results confirmed that climate change significantly affects crop production in the sampled countries. In particular, temperature, CO_2, and N_2O emissions have statistically significant negative effects on crop production, while a negligible negative relationship is seen with precipitation. Conversely, CH_4 emissions are positively associated with cereal production. Among the control variables, fertilizer use demonstrates a strong positive contribution to cereal yields, whereas an increase in cereal cultivation correlates with reduced productivity, possibly indicating diminishing marginal returns to land expansion.

The findings carry important policy implications. Given the adverse effects of rising temperatures, the development and dissemination of heat-resistant cereal crop varieties should be prioritized to bolster climate resilience and food security. Although CO_2 emissions appear to be positively associated with cereal output, this relationship may be misleading, as carbon-intensive agricultural practices can have adverse health and environmental consequences. Hence, future research and policy should emphasize sustainable, low-carbon cereal production systems.

Further, temperature-induced stresses such as increased evapotranspiration, altered cropping seasons, and irrigation demands suggest a need for adaptive agronomic strategies. These may include modified sowing calendars, short-duration crop varieties, and improved water-use efficiency (Ali & Erenstein, 2017). Historical evidence from African countries illustrates successful adaptation through flexible planting periods, diversification of income sources, soil conservation, and varietal adjustments in response to climate variability (Bryan, Deressa, Gbetibouo, & Ringler, 2009; Maddison, 2007).

In addition, the study identifies a negative association between rural population and cereal productivity, implying low labor efficiency in the agricultural sector. Enhancing farm labor productivity through mechanization, modern agronomic training, and entrepreneurship development could significantly strengthen the sector. Tailored climate policies, integrated with local adaptation capacities, are essential for enabling lower-middle-income countries to mitigate the adverse effects of climate change and sustainably improve cereal production.

6. LIMITATIONS AND FUTURE RESEARCH

This research selected 18 countries based on land productivity, with a threshold of 0.2 land productivity; other parameters for country selection were excluded. As climate variables, this paper used rainfall, temperature, CO_2, CH_4, and N_2O variables, while irrigation, technological adoption, and natural digester factors such as droughts, floods, and cyclones were ignored. For data analysis, this research employed a two-step system GMM model, which may suffer from small sample bias or weak instruments, potentially affecting the robustness of the results.

Future research could integrate additional climate and technological variables. It may also focus on other agricultural crops and expand the analysis to include more countries.

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Appendix

Table 1a. Country-wise cereal productivity in terms of land.

Name of the country	Cereal production (in million tons)	Area under cereal production (thousand KM2)	Productivity
Egypt	25.900	36.050	0.718
Bangladesh	59.800	97.260	0.615
Vietnam	50.300	108.000	0.466
China	642.000	1476.920	0.435
Hungary	19.300	46.960	0.411
Germany	49.100	123.870	0.396
Poland	39.900	117.260	0.340
UK	17.300	61.630	0.281
France	62.500	226.610	0.276
Myanmar	31.300	114.340	0.274
USA	456.000	1681.820	0.271
Philippines	28.300	108.000	0.262
Argentina	97.300	397.590	0.245
Pakistan	48.700	227.680	0.214
Italy	19.900	94.600	0.210
India	368.000	1765.260	0.208
Romania	20.200	97.740	0.207
Thailand	41.700	203.180	0.205
Turkey	46.800	240.550	0.195
Ethiopia	34.200	180.000	0.190
Brazil	144.000	800.480	0.180
Ukraine	61.000	347.670	0.175
Mexico	42.400	259.300	0.164
Spain	27.100	171.830	0.158
South Africa	18.100	124.330	0.146
Indonesia	67.700	478.050	0.142
Canada	72.100	519.200	0.139
Iran	24.700	197.790	0.125
Russia	143.000	1265.260	0.113
Kazakhstan	22.600	242.510	0.093
Nigeria	32.100	412.930	0.078
Australia	29.900	487.690	0.061